Analysis and Calculation of Three-dimensional Temperature Field of Inverter-fed Traction Motor

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***Abstract*-Due to the fact of immeasurable inner temperature of inverter-fed traction motor, three-dimension finite element model of part of rotor iron core and half a rotor bearing were established. The convective heat transfer coefficient between the air gap of motor and rotor surface were calculated according to the heat transfer and fluid mechanics theory. The influence of temperature rise on the stator and rotor resistance was considered for thermal loss calculation. The influence of the end of stator and rotor on axial temperature distribution was also taken into account. Then three-dimensional transient temperature field of the motor was calculated at the rated load. Temperature field with different loads was also computed. The aim has been to optimize the design with respect to the transient stresses. According to the contrastive analysis compared with other method, it demonstrated the accuracy of simulation model and thermal field calculation results.**

Keywords-Traction Motor; Temperature Field; Finite Element Analysis

I. INTRODUCTION

High-speed railway is considered as the best way of transportation for its characteristics of high efficiency, energy saving and environmental protection. With the rapid development of Chinese high-speed railway, the output power of traction motor increases significantly. Due to the limited space of the bogie as well as the maximum output voltage of converter switching device, the input voltage of traction motor cannot be further boosted. Moreover, the experience indicates that when the electrical insulation system is strengthened by one level, the output power of motor will correspondingly increase by 10% to 15%. So it's advisable to boost the output power of the traction motor by increasing the winding input current. However, large current will inevitably cause huge loss in the motor, which results in high temperature rise of each mechanical part (sometimes even reach up to 200 ℃ and above). In addition, in order to make full use of magnetic materials, the motor often designed at heavy electromagnetic load. So the loss of the motor increases dramatically and it leads to extra heat generated in the motor. Therefore, it has been gaining its popularity to limit the temperature rise by improving motor cooling system.

Temperature rise is an important indicator of performance for traction motor[1-3]. It also has a close relationship with motor's reliability and life. The traditional method of temperature calculating has several drawbacks. For example, it can only compute the average temperature rise of the motor , what's more, the accuracy is also not satisfactory to some extent. It has been acknowledged the accurate analysis of temperature field of traction motor is far more difficult due to the numerous factors such as motor structure, thermal properties of each part, the convection coefficient of motor enclosure, the width of air gap between stator and rotor, etc[4-8]. At the same time, the rotating rotor also makes the flow patterns of cooling gas in the rotor or between the stator and the rotor becomes more complex[9-10]. In this paper, three-dimension finite element model with one quarter rotor and overall stator was established to simulate the electromagnetic and thermal field of traction motor which has axial ventilating system. Electromagnetic field distribution and various losses were co-simulated by finite element software Ansoft and Ansys when the motor operated at the rated load. Then the steady-state thermal field of overall motor was computed when calculated loss was regarded as internal heat source. The impact on motor's mechanical structure by thermal stress at different loads was analyzed. Since the model is established based on the experiment data and test report under the action of the stresses applied, that gives us the opportunity to evaluate the life time of rotating motor with given system of stresses, the selected materials and the requested probability of failureless system operation.

II. NUMERICAL CALCULATION ON ELECTROMAGNETIC AND TEMPERATURE FIELD OF TRACTION MOTOR

A. Simulation Model

In this paper, a high-power traction motor with rated output power of 300kW was selected as the simulation model. Then the three-dimensional calculation model was established to analyze its electromagnetic and temperature field. Simulation parameters of traction motor were given in Table I. Two dimensional and three dimensional simulation model of traction motor were shown in Fig. 1 and Fig. 2 respectively.

TABLE I SIMULATION PARAMETERS OF TRACTION MOTOR

Rated parameters	Value
Rated power(kW)	300
Rated voltage(V)	2000
Frequency(Hz)	140
Rated speed(rpm)	4140
Outer and inner diameter of stator(mm)	Ø480-Ø310
Outer and inner diameter of rotor(mm)	Ø306-Ø80
Diameter and number of vents(mm)	Ø24-8 vents
Gauge of rotor bars(mm)	double layer, 1.5×5.5

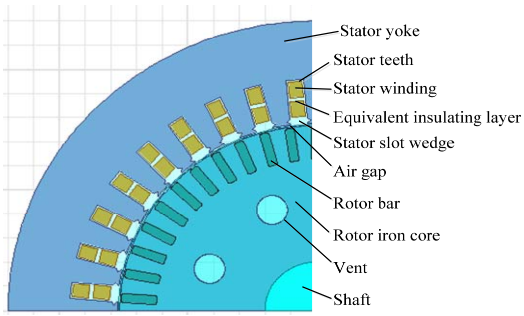

Fig. 1 Two dimensional simulation model of traction motor

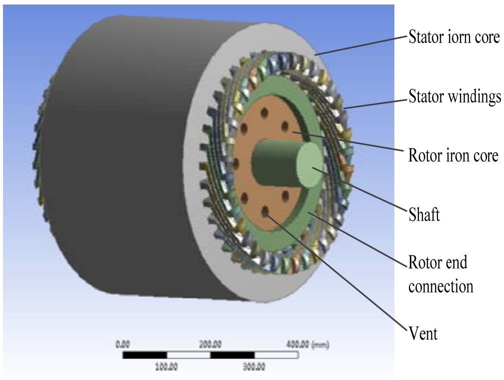

Fig. 2 Three dimensional simulation model of traction motor

B. Differential Equation of Heat Conduction Process and Its Boundary

When it comes to isotropic media, the thermal conductivity coefficient is usually regarded as constant. In the Cartesian coordinate system, differential equations of three-dimensional transient heat conduction and its boundary are listed as Eq. (1).

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right)+q=\rho c\frac{\partial T}{\partial t}$$

$$S_1: T=T_0$$

$$S_2: k\frac{\partial T}{\partial n}=-q_0 \tag{1}$$

$$S_3: k\frac{\partial T}{\partial n}=-\alpha(T-T_e)$$

Where T is the transient temperature of the object. $T_0$is the given temperature as boundary.T_e is the temperature of surrounding medium k_x, k_y, k_z are component of thermal conductivity in x,y and z direction.q is heat source density.q_0 is total heat flux which conducts through surface s_2. n is normal vector at boundary. α is coefficient of heat transfer.k is thermal conductivity.ρ is density of the object.c is specific heat capacity.

C. Internal Heat Generation

When the motor rotates, the magnetic material and copper windings will inevitably cause energy loss. On the one hand, the loss has great influence on the efficiency of the motor. On the other hand, it will eventually convert to thermal energy which raises the temperature of inner part of the motor. Therefore, accurate calculation of the loss of motor is an important prerequisite for temperature field analysis. Theoretically, the total loss of the motor can be divided into several parts which is shown in Eq. (2).

$$P_0=P_{Cu_1}+P_{Cu_2}+P_{Fe}+P_{mec}+P_{\Delta} \tag{2}$$

Where P_0 is total loss of traction motor.p_{Cu1} is stator copper loss. p_{Cu2} is rotor copper loss.p_{fe} is stator iron loss.p_{mec} is mechanical loss caused by rotor shaft bearing friction and fan windage.p_{Δ} is stray loss by higher harmonic.

Various losses in traction motor were computed using finite element analysis software according to iterative calculations when the motor operated at rated load. Then transient loss of double-layer stator windings named No.1-No.36 and rotor bars were shown in Fig. 3 and Fig. 4. In order to save the computing time, a quarter of rotor bars named No.1-No.12 were selected.

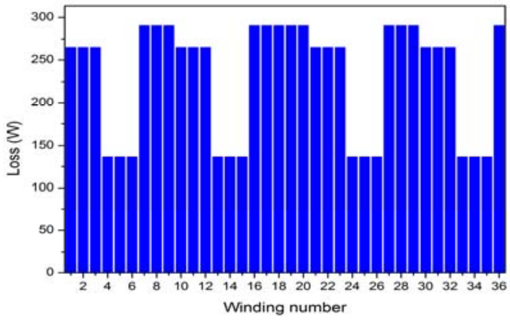

Fig. 3 Transient loss of stator windings

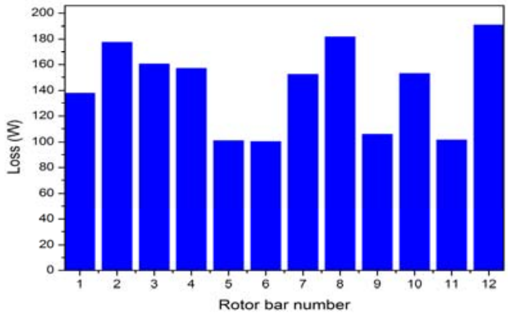

Fig. 4 Transient loss of rotor bars

TABLE II CALCULATION RESULT OF LOSS IN TRACTION MOTOR

Loss type	Value
Copper loss of stator windings(W)	7479.17
Copper loss of rotor bars(W)	6339.52
Iron core loss(W)	3717.74
Friction and windage loss(W)	2273.29
Stray loss(W)	3000

D. Convection Coefficient of Each Part in Traction Motor

At present, Kapton-FCR corona resistant polyimide film is mainly used in high-power traction motor to constitute Veridur - Plus Insulation System. The thin films are usually over-lapped up to 21mm plus with mica and glass belt to strengthen the entire mechanical intension. So it's obvious that the stator windings are commonly wrapped up by various types of materials with different thermal conductivity. The thermal conductivity of combination materials can be calculated by Eq. (3).

$$\lambda=\frac{\prod_{i=1}^{n}\lambda_i(\sum_{j=1}^{n}\delta_j)}{\sum_{i=1}^{n}(\lambda_i\prod_{j=1,j\neq i}^{n}\delta_j)} \tag{3}$$

Where λ_i is the thermal conductivity of insulating materials. δ_i is the thickness of each layer of insulating film.

Convection coefficient of ventilation groove in rotor is expressed in Eq. (4).

$$\lambda_r=54.9(\frac{30}{l})^{0.256}r^{0.088}(\frac{\omega}{10})^{0.832} \tag{4}$$

Where l is axial length of cooling ducts. r is hydraulic radius. ω is air speed of in the ducts.

Convection coefficient of stator slot can be calculated in Eq. (5).

$$a = 0.038\,\mathrm{Re}^{0.8}\,\varepsilon_1 \frac{\lambda}{d} \tag{5}$$

Where ε_1 is coefficient of short tube effect. λ is thermal conductivity. d is equivalent diameter. Re is Reynolds number of cooling air in slots.

In this paper, equivalent convection coefficient λ_g was proposed to describe thermal exchange capacity of the flowing air in the air gap. It was important to ensure the equal transferred heat between still air of the flowing air so that the flowing air can be regarded as still. According to this method, equivalent convection coefficient was used to evaluate performance of heat exchange of cooling air. Reynolds number of cooling air is shown as Eq. (6).

$$\mathrm{Re}_g = \pi D_2 g \frac{n}{60\gamma} \tag{6}$$

Where D_2 is outer diameter of rotor. n is motor rotating speed. γ is coefficient of dynamic viscosity of air, which equals $14.8\times10^{-6}\,\mathrm{m^2/sec}$ at 20˚C.

The critical Reynolds number is shown as Eq. (7).

$$\mathrm{Re}_{cr} = 41.2\sqrt{\frac{D_{i1}}{g}} \tag{7}$$

Where D_{i1} is stator's inner diameter.

When the Reynolds number of cooling air is smaller than critical Reynolds number, the flow pattern of cooling air tends to be laminar flow. So the equivalent convection coefficient equals to that of stagnant air approximately. Otherwise, the cooling air tends to be on flow. The equivalent convection coefficient is calculated by Eq. (8).

$$\lambda_g = 0.0019\eta^{-2.9084}\,\mathrm{Re}_g\, 0.4614\ln(3.33361\eta)$$
$$\eta = \frac{D_2}{D_{i1}} \tag{8}$$

III. ANALYSIS OF ELECTROMAGNETIC FIELD AND TEMPERATURE FIELD

A. *Calculation Results of Electromagnetic Field*

The magnetic field of traction motor can be plotted at the rated load, which is shown in Fig. 5. The maximum magnetic flux density is located at the teeth of iron core which is up to 2.22T.

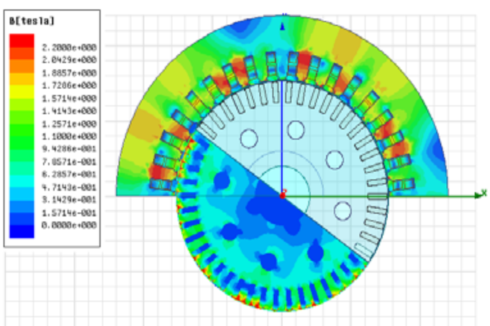

Fig. 5 Magnetic flux density of traction motor at rated load

In order to analyze the flux density at any point in the motor, semicircle lines are marked on the stator and rotor core as measuring path. The simulation results show that the flux density of rotor core is relatively higher compared with that of stator core at rated load. When the distortion and harsh peaks of magnetic flux density are ignored, the maximum flux density at the teeth of rotor core and stator core are 1.75T and 1.4Trespectively. Correspondingly, the value of yoke is 1.55T and 1.25T.

B. *Calculation Results of Temperature Field*

According to the model mentioned above, the static temperature field was analyzed. Due to the limited thermal conductivity of air between stator and rotor, the temperature field of stator and rotor can be calculated separately to simplify the calculation process. The temperature field of stator was plotted in Fig. 6.

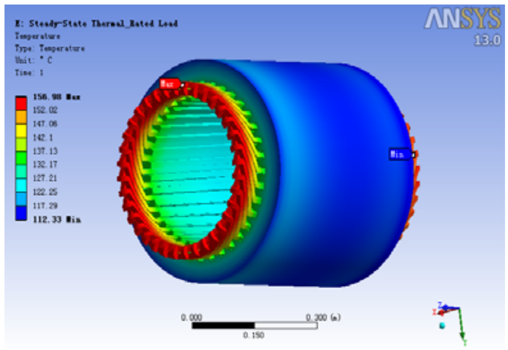

Fig. 6 Temperature field of overall stator at rated load

From the simulation results we can see the average temperature of stator core and windings were 138℃ and 146.2℃ respectively. This is mainly due to the fact that the copper loss of stator winding is the main heat source which is twice as much as the core loss approximately. Moreover, the forced external cooling air leads to temperature difference between inlet and outlet of stator ventilating ducts. In Fig. 6 the inlet of ducts located in the left hand of stator. The temperature of yoke and teeth of stator core along axial direction is shown in Fig. 7.

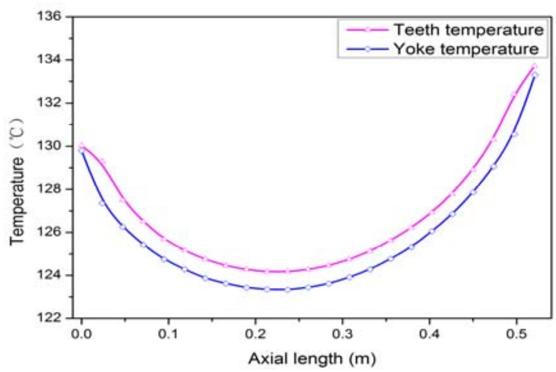

Fig. 7 Temperature of stator iron core along axial direction

Just as shown in Fig. 7, the average temperature of teeth and yoke are 126℃ and 124℃. The lowest temperature point is located at the axial central point in the motor stator while the highest temperature region is located at the end of each winding. This is due to the fact that traction motors are completely exposed in the open air when the locomotive operates at the high speed. The high-speed air flows on the motor enclosure and thus increases the convection coefficient. So it's conductive to transfer the heat from inner part to outside.

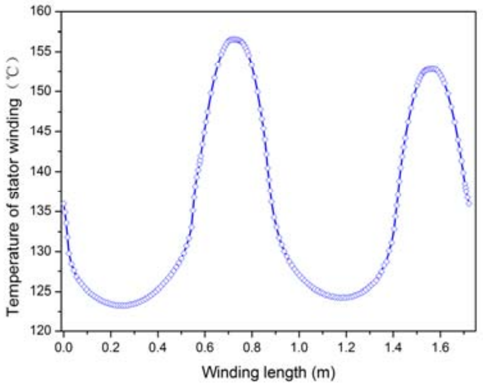

Fig. 8 Temperature of stator windings along the outter edge

Fig. 8 shows the temperature distribution along the outer edge of stator windings with significant change at different points. The highest temperature point is located at the end of windings in the outlet of ventilation ducts which reaches up to 156℃. However, the temperature is relatively low in the straight part of the winding which is close to that of stator iron core. The temperature at the end of windings in the inlet of ventilation ducts is 154℃ which is lower than that of outlet. It's mainly because the inner part of stator is located in the closed space. At the same time, too many ends of winding turns definitely obstruct the flow cooling air. All these things worsen the effect of heat dissipation.

The total heat flux of teeth and yoke of stator is shown in Fig. 9. The maximum heat flux appeared at the yoke of stator which are 40000W/m^2 and 38000W/m^2 at the inlet and outlet respectively. However, the heat flux of teeth is relatively lower. This is due to fact that the flow pattern of cooling air between the stator and rotor is on flow which means the air had good thermal insulation property. Therefore, the cooling capacity of the teeth of stator greatly reduces.

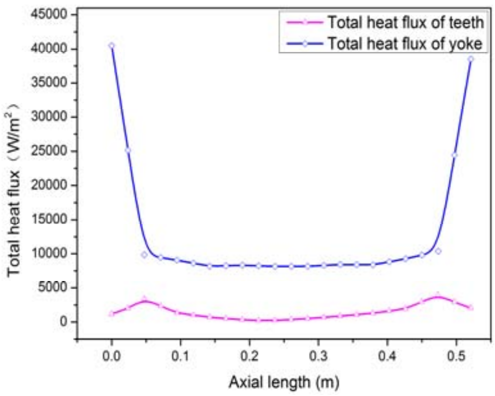

Fig. 9 Total heat flux of stator iorn core

Since there are eight vents in the rotor core, it will take much time to generate large amount of meshes and iteration calculation. So a quarter of the rotor was chosen as temperature solution region. Fig. 10 indicates the temperature of rotor when the motor operates at the rated load. It can be seen obviously that the temperature of rotor region is much higher than that of stator under the same condition. The highest temperature point is located at the central part of the rotor bars and the end connection ring which both reaches approximately 178℃. The difference in temperature between rotor iron core and rotor bars is rather small. What's more, there is significant temperature difference in the air gap when it reaches 40℃.

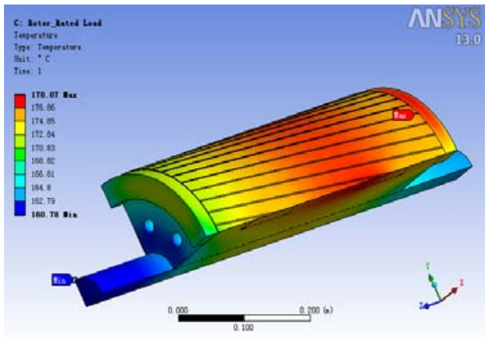

Fig. 10 Temperature field of overall rotor at rated load

Fig. 11 shows the temperature field of rotor along the axial direction. It can be seen clearly that there is a great change in the temperature of the teeth, yoke and the iron core of rotor. The maximum and minimum temperature are 177.88℃ and 171.69℃ respectively. The rotor bars have the highest temperature while the yoke with the lowest one. More heat is generated in the end connection rings because they are welded with the rotor bars which results in small resistance at the joint points. Fig. 12 indicates the temperature distribution of rotor along the radial direction. The tendency of temperature at the inlet and outlet of vents appeared to be similar. This is mainly because eight vents are arranged near the yoke of rotor centered with the shaft. When the rotor rotates at the high speed, the convection coefficient of iron core increases sharply. So the effect of heat dissipation can be enhanced significantly.

Fig. 13 shows the total heat flux of rotor. The maximum heat flux is located at the yoke of rotor with average value of 6000W/m^2. The heat flux of rotor bars and teeth are uneven which are both lower than that of yoke (4500W/m^2). The flow pattern of cooling air has great influence on the temperature distribution. So the vents in rotor are main paths of thermal energy.

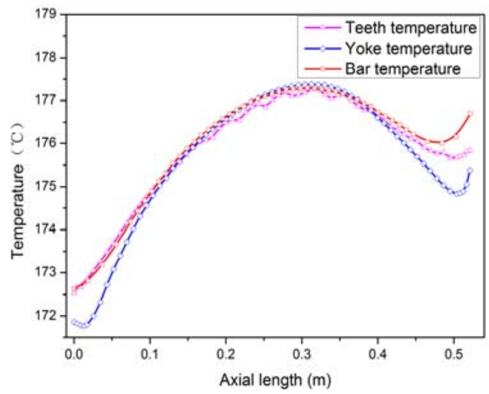

Fig. 11 Temperature of rotor iron core along axial direction

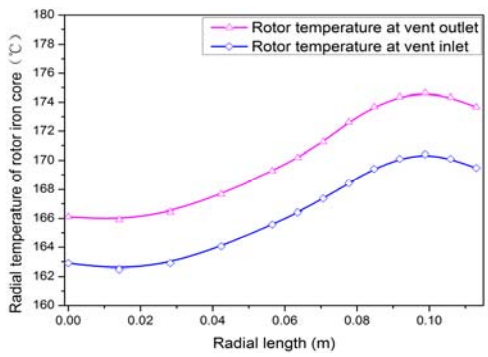

Fig. 12 Temperature of rotor iron core along radial direction

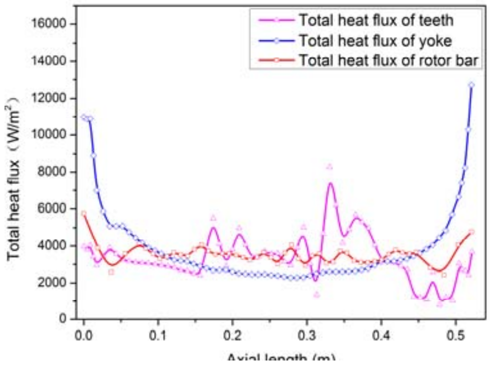

Fig. 13 Total heat flux of rotor iorn core

In most type tests of motor manufacturers, windings' resistance was measured to calculate motor temperature. In this paper, static temperature experiment was conducted using conventional method by measuring the temperature rise of vents in the motor. When the vent outlet temperature is without change, the corresponding temperature rise of motor seems to be stable.

$$h \cdot \Delta T_1 = C_{th} \cdot \Delta T_2 \tag{9}$$

Where h is convection coefficient between copper windings and cooling air. ΔT_1 is temperature difference between stator windings and inlet air. C_{th} is heat capacity of air. ΔT_2 is temperature rise of inlet air and outlet air.

Table III gives the comparison between calculation results and test results.

TABLE III COMPARISON BETWEEN SIMULATION AND TEST RESULTS

Test data	Type tests	Field tests
Vent inlet temperature (℃)	37	28
Vent outlet temperature (℃)	83	77
Temperature rise of vents (℃)	46	49
Temperature rise calculated by resistance method (℃)	138	149
Computing error	2.9%	4.6%

IV. CONCLUSIONS

The maximum magnetic flux density is located at the teeth of iron core when the motor operates at the rated load. The flux density of rotor core is relatively higher compared with that of stator core.

The highest temperature point is located at the end of windings in the outlet of ventilation ducts. However, the temperature is relatively low in the linear part of the winding which is close to that of stator iron core.

The temperature of rotor region is much higher than that of stator under the same condition. The highest temperature point is located at the central part of the rotor bars and the end connection ring. There is less difference in temperature between rotor bars and iron core. Rotor vents plays an increasingly important role in heat dissipation.

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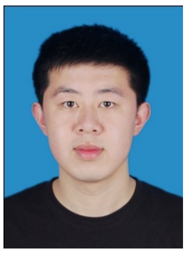

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